Precision Measurements using Atomic Systems

E.A. ALDEN
Leanhardt Lab
Department of Physics, University of Michigan


http://www.umich.edu/aehardt
So what do you do?
Light Interacts with Matter

\[ ^1D_2 \quad \text{to} \quad ^3S_1 \quad \text{to} \quad ^3P_2 \quad \text{to} \quad ^3P_0 \quad \text{to} \quad ^1S_0 \]

- Transition from \(^1D_2\) to \(^3S_1\): 579.1 nm
- Transition from \(^1P_1\) to \(^3S_1\): 185 nm
- Transition from \(^3P_2\) to \(^3S_1\): 296.7 nm
- Transition from \(^3P_2\) to \(^3P_0\): 404.7 nm
- Transition from \(^3P_0\) to \(^1S_0\): 518 nm
- Transition from \(^1P_1\) to \(^3P_1\): 233.1 nm
- Transition from \(^3P_1\) to \(^1S_0\): 365 nm

Total energy difference: 1621 THz
What is a clock?
Some Examples

Mechanical Clocks
• Pendulum Clock
• Quartz Clock

Atomic clocks
• Optical clocks

Sr Optical Atomic Clock Credit: Jun Ye Group
Why Atomic Clocks?

EM frequencies
Atoms are stable resonators
The Internet Told Me So…

The second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom.
The Internet also said...


It is the most accurate realization of a unit that mankind has yet achieved...
How good is a clock?

\[ \sigma(\tau) = \left\langle \frac{\Delta \nu}{\nu} \right\rangle \]
History of Clocks

\[ \sigma(\tau) = \left\langle \frac{\Delta \nu}{\nu} \right\rangle \tau \]

THE ELECTROMAGNETIC SPECTRUM

Penetrates Earth Atmosphere?
Wavelength (meters)

<table>
<thead>
<tr>
<th>Radio</th>
<th>Microwave</th>
<th>Infrared</th>
<th>Visible</th>
<th>Ultraviolet</th>
<th>X-ray</th>
<th>Gamma Ray</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^3)</td>
<td>(10^{-2})</td>
<td>(10^{-5})</td>
<td>(0.5 \times 10^{-6})</td>
<td>(10^8)</td>
<td>(10^{-10})</td>
<td>(10^{-12})</td>
</tr>
</tbody>
</table>

About the size of...

- Buildings
- Humans
- Honey Bee
- Pinpoint
- Protozoans
- Molecules
- Atoms
- Atomic Nuclei

Frequency (Hz)

Temperature of bodies emitting the wavelength (K)

- 1 K
- 100 K
- 10,000 K
- 10 Million K
Where is $^{133}\text{Cs}$?

\[1621 \text{ THz} \quad \uparrow \quad 9,192,631,770 \text{ Hz} \quad \downarrow \quad \square \quad 0.009 \text{ THz}\]

\[\text{J}=1/2 \quad \text{I}=7/2 \quad \text{F}=4 \quad \text{F}=3\]
Neutral Hg

\[ ^3P_1 \quad ^3P_0 \quad \text{---} \quad \text{---} \quad 1129 \text{THz} \quad 266 \text{nm} \]

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{196}$Hg</td>
<td>0</td>
</tr>
<tr>
<td>$^{198}$Hg</td>
<td>0</td>
</tr>
<tr>
<td>$^{199}$Hg</td>
<td>1/2</td>
</tr>
<tr>
<td>$^{200}$Hg</td>
<td>0</td>
</tr>
<tr>
<td>$^{201}$Hg</td>
<td>3/2</td>
</tr>
<tr>
<td>$^{202}$Hg</td>
<td>0</td>
</tr>
<tr>
<td>$^{204}$Hg</td>
<td>0</td>
</tr>
</tbody>
</table>
Make $\Delta \nu$ small

$$\sigma(\tau) = \left\langle \frac{\Delta \nu}{\nu} \right\rangle_\tau$$

- Narrow linewidth transition
- Narrow linewidth laser
- Large number of addressed resonators
- Long coherence times
- Long measurement times
- Laser excitation geometry (transit broadening)
- So on….

### TABLE 1.

<table>
<thead>
<tr>
<th>Physical Effect</th>
<th>Bias</th>
<th>Type B Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitational Red shift</td>
<td>+179.95</td>
<td>0.03</td>
</tr>
<tr>
<td>Second-Order Zeeman</td>
<td>+180.91</td>
<td>0.025</td>
</tr>
<tr>
<td>Blackbody</td>
<td>-22.84</td>
<td>0.28</td>
</tr>
<tr>
<td>Microwave Amplitude Shift</td>
<td>-0.05</td>
<td>0.15</td>
</tr>
<tr>
<td>Spin Exchange (low density)</td>
<td>(-0.32)$^*$</td>
<td>(0.17)$^*$</td>
</tr>
<tr>
<td>AC Zeeman (beaters)</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Cavity Pulling</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Rabi Pulling</td>
<td>$10^4$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Ramsey Pulling</td>
<td>$10^4$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Majorana Transitions</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Fluorescence Light Shift</td>
<td>$10^2$</td>
<td>$10^2$</td>
</tr>
<tr>
<td>Cavity Phase (distributed)</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Second-Order Doppler</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>DC Stack Effect</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Background Gas Collisions</td>
<td>$10^3$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Bloch-Siegert</td>
<td>$10^3$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>RF Spectral purity</td>
<td>$3 \times 10^3$</td>
<td>$3 \times 10^3$</td>
</tr>
<tr>
<td>Integrator offset</td>
<td>0</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Total Type B Standard Uncertainty: 0.33

*For information purposes only. Not used in total, see section 1-B for details.

Table 1 – The list of known frequency biases for NIST-F1. This includes both the magnitude of the biases as well as the uncertainty of each individual contribution to the final uncertainty.
Choose Transition Wisely

"forbiddenness"

natural linewidth $\Delta \nu$
Optical Clock Level Structure

$^3P_0$  

$^1S_0$
$^{199}$Hg  $I=1/2$

$^3P_1$  $^3P_0$  $^1S_0$

$\tau=115(6)\text{ns}$
$\gamma=1.3\text{ MHz}$

$\tau=1.51\text{s}$
$\gamma=0.1\text{ Hz}$

Even Narrower Transition?

\[ ^3P_1 \quad ^3P_0 \]

\[ ^1S_0 \quad \text{M1} \quad \text{E1} \]
Even Narrower Transition?

$^3P_1 \rightarrow ^3P_0$

$2 \times 564 \text{ THz}$

$^1S_0 \rightarrow \Delta$

M1

E1
EM waves

Electromagnetic Wave

- Magnetic field
- Electric field

λ
Advantages

• Linewidth preserving access to $^3P_0$ level
• Doppler-Free Spectroscopy with room temperature atoms.
• Vapor cells have high densities of atoms
Doppler Broadening

![Diagram of Doppler Broadening](http://www.umich.edu/aehardt)
Doppler-Free Spectroscopy
Drawbacks: Transition Rates

\[ R_{1\gamma} \propto \left\langle ^3P_1 | \mu | ^1S_0 \right\rangle_{E1}^2 I \]

\[ R_{2\gamma} \propto \frac{\left\langle ^3P_0 | \mu | ^3P_1 \right\rangle_{M1}^2}{\Delta^2} \left\langle ^3P_1 | \mu | ^1S_0 \right\rangle_{E1}^2 I^2 \]
Off-the-shelf Laser
Narrow Linewidth Laser

• <10 kHz linewidth 1062nm @ ~10mW
• Fiber amplifier 10 mW -> 50W
• Single pass PPMgO:SLT SHG

10-25W @ 531nm
Green Laser Pointers

- 5mW w/ 1.1mm dia beam -> 0.58 W/cm²
- Human eye blink time – 200ms
- Damage threshold – > 0.005 W/cm²

- We’re building a laser -> 77 W/cm²
And the point of all this…

when ↔ where

Recalculating
How do we fit into this puzzle?

- Explore this level structure transition
- Make clocks portable
- Map the geoid w/ 30m gravitational redshift resolution

$$\frac{\Delta \nu}{\nu} \approx 10^{-16}$$
Frequency Comparison of Two High-Accuracy Al\(^{+}\) Optical Clocks

C. W. Chou, * D. B. Hume, J. C. J. Koelemeij, † D. J. Wineland, and T. Rosenband

Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305, USA
(Received 23 November 2009; published 17 February 2010)

We have constructed an optical clock with a fractional frequency inaccuracy of \(8.6 \times 10^{-18}\), based on

\[
\frac{\Delta \nu}{\nu} = 8.6 \times 10^{-18}
\]
Fig. 3 Gravitational time dilation at the scale of daily life.
C W Chou et al. Science 2010;329:1630-1633
Leanhardt Research Group

Aaron Leanhardt (PI)
Jinhai Chen (post-doc)
Yisa Rumala (grad)
Jeongwon Lee (grad)
Emily Alden (+1) (grad)
Kaitlin Moore (post-bac)

Not Shown:
- Charlie Steiner (undergrad)
Hg Level Structure & $^3S_1$ Branching Ratios

Collision NH$_3$

\[
\begin{align*}
\text{Hg}(^1S_0) + h\nu &\rightarrow \text{Hg}(^3P_1) \\
\text{Hg}(^3P_1) &\rightarrow \text{Hg}(^1S_0) + h\nu \\
\text{Hg}(^3P_1) + \text{NH}_3 &\rightarrow \text{Hg}(^3P_0) + \text{NH}_3 \\
\text{Hg}(^3P_1) + \text{NH}_3 &\rightarrow \text{Hg}(^1S_0) + \text{NH}_2 + \text{H} \\
\text{Hg}(^3P_0) + \text{NH}_3 &\rightarrow [\text{Hg} \cdot \text{NH}_3]^* \\
[\text{Hg} \cdot \text{NH}_3]^* &\rightarrow \text{Hg} + \text{NH}_3 + h\nu'.
\end{align*}
\]

Mercury-Sensitized Luminescence of NH$_3$ and ND$_3$


Chemistry Dept., University of Canterbury, Christchurch, New Zealand

Received 11th May, 1970
See Under Rug…

- Power broadening
- Stark shifts
- Rayleigh scattering

Mike Mosedale
Light Interacts with Matter
Allan Deviation

\[ \sigma_y(\tau) \approx \frac{\Delta \nu}{\nu} \sqrt{\frac{1}{N\tau}} \]
## Clocks

<table>
<thead>
<tr>
<th>Technique</th>
<th>$\sigma_{\mu}$ @ 24 hours</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pendulum</td>
<td>10 s</td>
<td>1656</td>
</tr>
<tr>
<td>Chronometer</td>
<td>0.4 s</td>
<td>1761</td>
</tr>
<tr>
<td>Quartz</td>
<td>$10^{-4}$ s</td>
<td>1927</td>
</tr>
<tr>
<td>Cs</td>
<td>$4.3 \times 10^{-11}$ s</td>
<td>1952</td>
</tr>
<tr>
<td>Rb</td>
<td>$10^{-6}$ s</td>
<td>1958</td>
</tr>
<tr>
<td>Al$^+$</td>
<td>$7.4 \times 10^{-13}$ s</td>
<td>2010</td>
</tr>
</tbody>
</table>